

Interpretation of Si concentrations in lake sediments: three case studies

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Abstract The biogenic Si concentration in a sediment can be determined as the non-detrital Si concentration by normalization of the total Si concentration with Al. This procedure is based upon the assumptions that (1) that Al exists predominantly in detrital, i.e. minerogenic, particles and (2) that biogenic Si (mainly diatom frustules) is the dominating non-detrital Si phase. This paper focuses on the reasons for the variations of the non-detrital Si concentration in these lake sediments. Data from three lakes are presented, representing three principally different cases regarding the Si concentration. The processes controlling the concentrations of detrital and non-detrital Si are discussed.

Keywords detrital matter · Lake sediment · Silicon · Sweden

Introduction

Sediments are made up of different phases, such as mineral particles and organic matter. Another important phase is biogenic Si, mainly as diatom frustules. In lakes, biogenic Si often constitutes a significant part of the sediment. Engstrom and others (1985; Harvey's Lake, Vermont) and Conley (1988; Lake Michigan) have measured 10–15% biogenic Si in lake sediments, and in Lake Baikal, Stoermer and others (1995) have detected concentrations of up to 60% biogenic Si.

There are principally two types of particles that make up the total Si concentration: detrital Si (i.e. Si in rock fragments formed by mechanical weathering in the drainage area) and diatom Si (other biogenic Si phases are often of minor importance). The concentration of Si from these types of particles may vary as a result of different processes. The concentration of diatom Si is dependent on diatom production and dissolution of diatom frustules.

The diatom production may in turn be dependent on environmental factors, for example trophic status and concentrations of trace metals. Land use changes may affect the sedimentation of detrital Si. In this paper, we show in three principally different cases how the Si concentration in a lake sediment may vary, and we discuss the possible mechanisms behind the variations.

To be able to study the variations of diatom Si and detrital Si in a sediment, the Si concentration is normalized. The normalization implies that a constant relationship between Si and a certain element (for example Al or Ti) is assumed in the weathered rock fragment phase. All Si in excess of this Si/Al (or Si/Ti) ratio is assumed to be diatom Si. If the Si/Al ratio in the sediment is equal to that in the local detrital material and without significant variations, detrital material is the sole major Si phase in the sediment. If, on the other hand, the Si/Al ratio is higher, diatoms constitute an important part of the total Si. By studying variations in the Si/Al ratio with depth, one can monitor changes in diatom production. A decreasing concentration of non-detrital Si must, however, not infer a decreasing diatom production. If the sedimentation rate of another phase, for example detrital or organic matter, increases, the non-detrital Si will simply be diluted. To be able to distinguish between actual decreases in sedimentation flux and concentration decreases caused by dilution effects, one must gain knowledge about possible changes in the overall sedimentation rate.

Materials and methods

Study area

The three lakes studied all lie within the drainage area of the Kalix River, northern Sweden (Fig. 1). Coniferous forests (55–65%) and peatland (16–20%) cover most of the area. Lakes cover ~4% of the area. Less than 1% of the area is cultivated (Hjort 1971). Till is the dominant soil type (Fromm 1965), whereas bedrock exposure is sparse (<1% of the total area). Precambrian rocks, mainly 1.9- and 1.8-Ga-old granitoids, dominate the bedrock in the major part of the area (Ödman 1957; Gaál and Gorbatshev 1987).

Lake Sakajärvi is a small, rather shallow lake (maximum depth about 6 m, area 1.3 km²), situated 15 km SW of Gällivare. Close to Lake Sakajärvi, the copper mine Aitik

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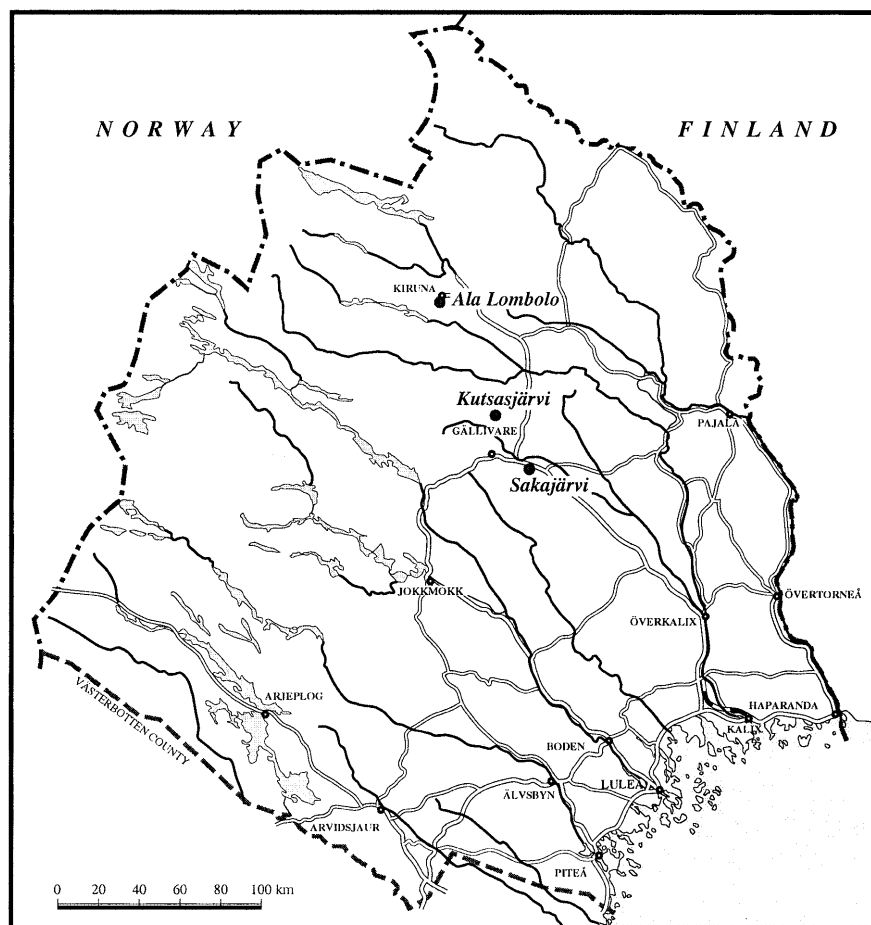


Fig. 1

Map of the study area, showing the locations of the studied lakes

is located. It is an open-pit mine, primarily mined for chalcopyrite. Pyrite, magnetite and pyrrhotite are also present. The waste rock heaps are located within the drainage area of the lake. The production at Aitik started in 1967.

Lake Ala Lombolo is a small lake, only 0.3 km², with a maximum depth of approximately 2 m. It is located in Kiruna, very close to an iron mine. The mined ore mineral is primarily magnetite. Fluoroapatite and hornblende are abundant, whereas calcite, biotite, quartz, titanite, diopside, talc, albite and sulfides occur in minor amounts (Parak 1973). The waste rock heaps around the mine drain through Luossajoki into Lake Ala Lombolo and eventually into the Torne River. The Torne River, in turn, is connected to the Kalix River via the bifurcation Tärendö River. In addition to the effects from the mine, municipal sewage, which was drained into the lake until 1967, has largely influenced the water chemistry of Lake Ala Lombolo.

Lake Kutsasjärvi (3.1 km², depth at sampling point 7 m, maximum depth 36 m), 30 km N of Gällivare, is relatively undisturbed by human activities.

Methods

For the sediment sampling, we used a modified Kajak gravity corer (Blomqvist and Abrahamsson 1985). The sampling took place at three different occasions from July

to August 1995. The cores were sliced into 0.5- to 2-cm-thick subsamples immediately after sampling. Porewater was extracted and filtered through 0.45- μ m Millipore filters using a vacuum pump, and analysed for Si by inductively coupled plasma-atomic emission spectrometry (ICP-AES). To prevent oxidation of the reduced phases, we performed the pore water sampling in an Ar-filled glove box within 36 h of the sampling.

The sediment subsamples were freeze-dried, weighed and homogenized by grinding. Subsamples for diatom analysis were removed prior to grinding. For analysis of total Si, Al, Ti, P, Fe, Mn, Mo and V, 0.125 g of sediment was fused with LiBO₂ at 1,000 °C (Burman and others 1978). The bead thus formed was dissolved in 0.7 M HNO₃ and analysed by ICP-AES. Analyses of certified reference sediments showed that >90% of the certified concentrations was recovered. The instrumental precision (± 1 RSD for three replicate measurements on each sample was <0.5% for SiO₂ and Al₂O₃, and <1% for TiO₂. For analysis of As, Cr, Hg and Ni, 0.5 g of sediment was digested in 10 ml 7 M HNO₃ in a Teflon bomb and heated in a microwave oven for 60 min. The solution was centrifuged and diluted and finally the concentrations were determined by ICP-mass spectrometry (MS). Carbon and N were determined with an elemental analyser.

The quantitative diatom analysis was performed using microspheres according to Battarbee and Kneen (1982).

Freeze-dried sediment (4–10 mg) was treated with 10% HCl (to remove possible Fe or Mn oxides) and with 30% H₂O₂ (to oxidize organic matter). After the addition of a known amount of latex micro-spheres (mean diameter 9.7 μm) to the sample, an aliquot was dried on a coverslip at room temperature. Diatoms and microspheres were counted at a magnification of ×400–600. We did not count fragments consisting of less than half valves. The dissolved phase (filtered through 0.45-μm Millipore filters mounted in Geotech polycarbonate filter holders) in the water column was sampled during a time series from June to October 1995. Tubing was lowered through the water column to the sampling depth, and, using a peristaltic pump, the water was pumped up into acid-cleaned plastic cans and subsequently filtered. One or two samples were taken from each lake approximately once a week during this time period. In Lake Ala Lombolo, the sample was taken at mid-depth whereas, in Lake Kutsasjärvi and Lake Sakajärvi, two samples were taken on each occasion, at ~2.5 and 5.5 m depth, respectively. Dissolved Si, Ca, Mg, Na and K were determined by ICP-AES, Cl⁻ and SO₄²⁻ were determined by ion chromatography, and PO₄³⁻ was determined by colorimetry. Alkalinity was determined using an autotitrator. On each sampling occasion, we took one integrated water sample. This sample should represent the entire water column with respect to diatoms. From each sample, 10 ml was extracted and centrifuged at 4,000 rpm for 5 min. The supernatant was carefully decanted leaving the suspended phase behind in ~1 ml water. This procedure was repeated ten times until 100 ml had been centrifuged, resulting in a 100-fold enriched suspended phase. This sample was treated for diatom analysis in the same way as the sediment samples (see above).

To separate the detrital from the non-detrital Si, we normalized the total Si concentration with Al. When normalizing with Al, we assume that all Al derives from detrital material, and that there is a constant Si/Al ratio in detrital material. Thus, all Si in excess of this ratio is non-detrital. The variations of the Si/Al ratio in a sediment is a convenient way to study compositional variations regarding Si. When studying the Si/Al ratio, we do not have to bother about other phases, such as Fe oxides or organic matter, which may, by dilution, influence the absolute concentrations of Si and Al. The Si/Al ratio provides information about the nature of the Si. We can also calculate the absolute concentrations of the two Si phases. The non-detrital Si concentration was calculated using the following formula (Ingri and Widerlund 1994):

$$Si_{nd} = Si_{meas} - (Si/Al)_{detr} \times Al_{meas} \quad (1)$$

where Si_{meas} and Al_{meas} denote the measured concentrations of Si and Al, respectively, and $(Si/Al)_{detr}$ denotes the relationship between Si and Al in detrital material, principally originating from weathering of till. The average molar Si/Al ratio of till in the area of interest has been determined to 3.88 ± 0.22 (Öhlander and others 1991). In some cases, Al can become enriched by, for example, secondary mineral formation. Then it is more appropriate to

choose another element, for example, Ti, which is principally of detrital origin. For Lake Sakajärvi, we used Ti as a normalization element instead of Al (see below). The average molar Si/Ti ratio in till according to Öhlander and others (1991) is 89.2 ± 12.0 .

A potential problem when using normalization is sediment focusing, leading to a fractionation of the detrital material. A possible result of this fractionation is that Al (or Ti) no longer would be a representative measure of detrital material. However, in both Lake Kutsasjärvi and Lake Ala Lombolo, the Al/Ti ratio is fairly constant (27.4 ± 1.9 and 23.6 ± 0.6 , respectively) and shows no systematic variations with depth. Although sediment focusing and grain size fractionation may well occur, the constant Al/Ti ratios show that Al still is a good measure of detrital material in these sediments. Normalization with Al can, therefore, be used for these lakes.

Another potential problem is the assumption of a constant Si/Al ratio of detrital material. Sediment focusing of detrital particles during transport to and sedimentation in a lake may possibly lead to a sediment depleted in quartz and heavy minerals and enriched in micas and clay minerals. An unweathered granite, typical for the region (Lina granite: 20–25% quartz, 40–45% K-feldspar, 30–35% albitic plagioclase, 5% biotite) has a molar Si/Al ratio of 4.4. The Si/Al ratio of a totally quartz-depleted Lina granite is 3.1, and of pure biotite 2.9. Deviations of the Si/Al ratio of the detrital material in the actual sediment from the assumed detrital value, may be of importance for the calculation of non-detrital Si. Low total Si/Al ratios of the sediment (that is, where the Si is mostly detrital) result in larger calculation errors. The lake sediments studied here all have Si/Al ratios that are considerably higher than in the background detrital material (that is, they contain substantial amounts of biogenic Si). The high Si/Al ratios make the calculations less sensitive to deviating detrital Si/Al ratios. For example, in a sediment with a Si/Al ratio of 12, 67% of the Si is non-detrital using a detrital background ratio of 4, and 75% when using a background ratio of 3. A total SiO₂ concentration of 35% would then give non-detrital SiO₂ concentrations of 23 and 26%, respectively. This uncertainty interval does not preclude interpretations of variation of non-detrital Si at intermediate to high Si/Al ratios. At low Si/Al ratios, one has to be more cautious with interpretations of variations.

In Peinerud (1997), the concentration of non-detrital Si in sediments from Lake Kutsasjärvi and Lake Ala Lombolo was compared with the number of diatom valves. The observed correlations led to the conclusion that non-detrital Si is a good estimate of diatom concentration.

Results and discussion

Lake Kutsasjärvi

Lake Kutsasjärvi is relatively undisturbed by human activities, and is considered as normal regarding diatom production.

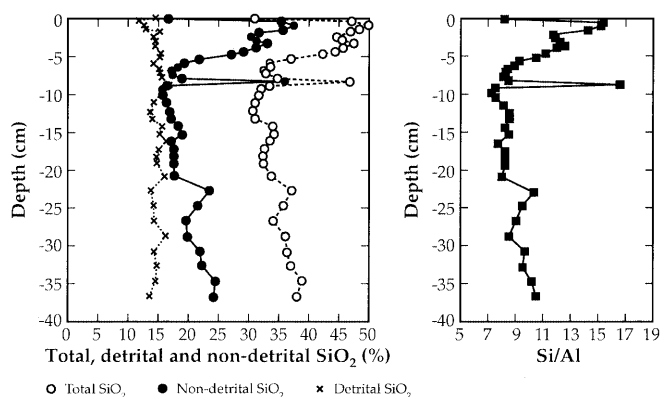


Fig. 2

Sediment from Lake Kutsasjärvi. **a** The concentrations of total, non-detrital and detrital SiO₂ vs depth. **b** The molar Si/Al ratio vs depth

The most prominent feature regarding Si in the sediment core from Lake Kutsasjärvi is the decreasing concentration of non-detrital SiO₂ from 37% (dry weight) at the surface to 15% at 10 cm depth, except for the low concentration in the very topmost layer (Fig. 2a). The decrease is probably caused by a gradual dissolution of diatoms. Between 10 and 20 cm, the concentration of non-detrital SiO₂ is relatively constant (~17%), and below 20 cm, the concentration tends to increase, reaching 25% at 37 cm depth. The concentration of detrital Si is almost constant throughout the core.

Lewin (1961) showed that metals such as Al and Fe can combine with diatom silica and affect either their dissolution rate or their final solubility. According to Nelson and others (1995), these metal ions, which can form highly insoluble hydroxides, possibly bind to hydroxyl groups at the surface of the hydrated amorphous silica. Van Benkom and others (1991) have showed that Al concentrations as low as 100 nM significantly decrease the dissolution rate and solubility of biogenic Si. In Lake Kutsasjärvi, the average concentration of filtered (<0.45 μm) Al is ~150 nM (unpublished data). Considering the geochemical similarities between Al, Fe and Mn, it is possible that

Fe and Mn can provide a similar protection against dissolution as Al does.

Fe and Mn are two important redox elements in lakes. There are differences in the redox chemistry of Mn compared with Fe, and this can result in a partial separation of Mn from Fe. Mn is usually more readily reduced (at a higher redox potential) than Fe, and Fe is much more rapidly oxidized than Mn. Consequently, much of the Mn supplied to the sediment will be solubilized and re-released to the water column, whereas the Fe will be more efficiently retained in the sediment. For a further discussion, see for example Davison (1985, 1993). The lower the redox potential in the sediment, the less Mn relative to Fe can be fixed in the sediment. Thus, the Mn/Fe ratio in the sediment is related to its redox conditions, and can therefore be used as an indirect measure of the redox potential.

For the top 10 cm of the Lake Kutsasjärvi sediment, there is a linear correlation ($R^2=0.99$) between Mn/Fe and non-detrital SiO₂ (Fig. 3a). We suggest two mechanisms that, although speculative, may explain this striking correlation. With the first alternative, we assume that Fe and Mn affect the dissolution of diatoms in a similar way as previously discussed for Al. As the redox potential decreases, Fe(III) is reduced to Fe(II) and Mn(IV) to Mn(II), and the metal hydroxide coating dissolves. Consequently, the dissolution rate of the diatom frustules increases as the environment becomes more and more reducing with increasing depth. Alternatively, the dissolution rate of biogenic silica may be controlled primarily by protective organic coatings. As these coatings become oxidized and dissolve, the dissolution rate increases (Lawson and others 1978). Simultaneously, the oxidation of organic matter in the absence of oxygen leads to a decreasing Mn/Fe.

Direct measurements of the redox potential using a Pt electrode gave the same indications as the Mn/Fe ratio (Fig. 3b). However, such measurements are associated with certain difficulties. One problem is that the pore water can easily become oxidized during the sampling procedure, even if an anoxic environment is provided for the pore water extraction. Often only very small pore water volumes can be extracted from the sediment samples,

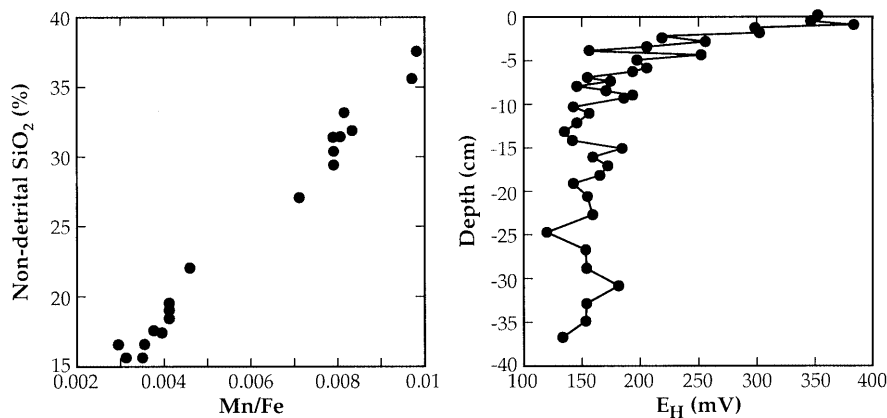


Fig. 3

a Concentration of non-detrital SiO₂ (%) plotted against the Mn/Fe ratio from 0 to 10 cm sediment depth. **b** The pore water redox potential (mV) in the sediment from Lake Kutsasjärvi

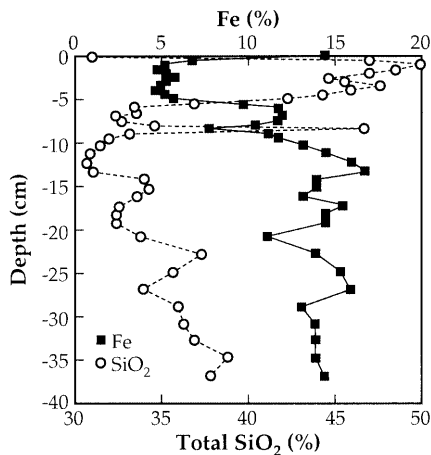


Fig. 4

The concentrations of Fe (%) and total SiO₂ (%) vs depth in the sediment from Lake Kutsasjärvi

and this might make the redox potential measurements more difficult. The method of using the Mn/Fe ratio as an estimation of the relative redox potential in one single sediment is not that sensitive to oxidation during the handling of the samples, because the amount of reduced (dissolved) phases is small compared with that of the oxidized (solid) phases. The Mn/Fe ratio may even be a more appropriate parameter than the redox potential in explaining the concentration of non-detrital Si because the latter method does not account for the oxidation kinetics, which also, in some way, may affect the dissolution rate of the diatom frustules.

The low total concentration of SiO₂ in the topmost layer can to a large extent be explained by dilution with Fe (Fig. 4), as predominantly non-detrital Fe, considering the relatively high Fe/Al ratio in this subsample. As can be seen from Fig. 2a the detrital SiO₂ concentration is fairly constant throughout the core, whereas non-detrital SiO₂ makes up between 50 and 75% of total SiO₂. Because only the non-detrital component has been diluted in the top sample, the detrital sedimentation flux must have increased relative to the non-detrital SiO₂ flux, which is illustrated by the low Si/Al ratio in the topmost layer (Fig. 2b). A possible reason for this is that relatively large amounts of detrital Si have been carried into the lake by the spring flood, and still dominated non-detrital Si in the surface layer at the time of sampling, in early summer.

Lake Sakajärvi

A dated (²¹⁰Pb) core, sampled on a previous occasion (Pontér and Ljungberg unpublished data), indicates that the sedimentation rate in Lake Sakajärvi has increased during the last few decades. Al is present in excess of Ti in the top 4 cm of the sediment compared with the Al/Ti ratio of detrital matter (Öhlander and others 1991). Not only the Al/Ti ratio, but also the absolute concentration of Al, is high in the surface layer, indicating the presence of non-detrital Al rather than a deficit of Ti. A possible

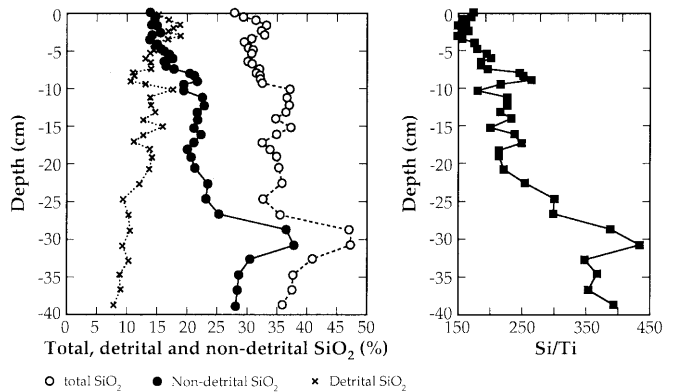


Fig. 5

Sediment from Lake Sakajärvi. **a** The concentrations of total, non-detrital and detrital SiO₂ vs depth. **b** The molar Si/Ti ratio vs depth

source of this non-detrital Al is precipitation or adsorption to particles in the water column, as more acid water, with a higher concentration of dissolved Al, enters the lake from surrounding mires. Because of the presence of non-detrital Al, Ti has been chosen as a normalization element instead of Al for Lake Sakajärvi.

The non-detrital SiO₂ concentration in the sediment declines from ~20% at a depth of ~12 cm to 15% at the sediment surface (Fig. 5a). Between 10 and 20 cm, the concentration of non-detrital SiO₂ is fairly constant (~22%), but below 20 cm it increases downward and reaches a maximum of 38% at a depth of 30 cm. The concentration of detrital SiO₂ increased from <10% at 40 cm depth to between 15 and 20% in the top 5 cm. Assuming a constant sedimentation rate of detrital material, the decreasing concentration of non-detrital Si between 12 cm depth and the surface could be interpreted as decreasing diatom production. Considering the dating, however, this decrease is mainly a result of dilution of the diatom frustules with another type of material. The molar Si/Ti ratio also declines towards the surface (Fig. 5b), implying an increase of detrital sedimentation, possibly of anthropogenic origin. As can be seen in Fig. 5a, the decrease of non-detrital SiO₂ is, to some extent, balanced by an increase of detrital SiO₂. The start of the decline of the non-detrital SiO₂ concentration correlates well in time with the onset of mining in Aitik in 1967. This implies that the increased sedimentation rate of detrital material can be related to the mining activities. Combining the dating of the previously sampled core with the porosity of the sediment, the sedimentation rate (expressed as g year⁻¹ cm⁻²) can be estimated. The porosity has been calculated as (mass of dry sediment)/(volume of wet sample x density), where the density has been given a value of 2.5 g/cm³. The annual fluxes of the different components can then be calculated as the total sedimentation rate multiplied by the concentration of the component in question. The total sedimentation rate (g year⁻¹ cm⁻²) thus obtained increased by 480% from a

depth of 8 cm (~15 years old) to 4 cm (~5 years old). Although detrital sedimentation (TiO_2) had increased by 620%, the non-detrital sedimentation of Si had only increased by 350%. Consequently, the non-detrital Si became more diluted, and its concentration declined. The sedimentation fluxes of non-detrital K_2O , Al_2O_3 and MgO , on the other hand, seem to have increased considerably more than the total sedimentation increase during the same time period, whereas the flux of non-detrital Na_2O tends to be decreasing. Both non-detrital K_2O and MgO correlates well ($R^2=0.96$ and 0.92 , respectively) with non-detrital Al_2O_3 in the sediment, suggesting a common origin.

The above interpretation uses sedimentation rate and porosity. The determination of both these variables may be rather uncertain. Therefore, we will not exclude the possibility that the decreasing concentration of non-detrital Si is a result of a decreasing diatom production.

In contrast to Lake Kutsasjärvi, there is no correlation between the Mn/Fe ratio and the concentration of non-detrital SiO_2 in Lake Sakajärvi. A plausible reason for this is that the dilution effect described above overshadows the preserving effect that metal hydroxide coatings can exert on diatom frustules.

There is another decrease in non-detrital Si concentration between 30 and 20 cm depth in the sediment core from Lake Sakajärvi (Fig. 5a). The concentrations of Al_2O_3 , TiO_2 , CaO , K_2O , MgO and Na_2O all increase during this interval, but porosity also increases from ~94 to 97%. The total sediment flux ($\text{g year}^{-1} \text{cm}^{-2}$) has thus decreased during the time interval corresponding to this deposition. Accordingly, this decrease in non-detrital Si concentration could be because its sedimentation flux has decreased more than the fluxes of most other components. The causes for these decreases are not clear.

Lake Ala Lombolo

In Lake Ala Lombolo, the Si/Al ratio in detrital matter used elsewhere in this paper, 3.88, seems to be somewhat too high. The lowest molar Si/Al ratio in this sediment core was 3.47. Therefore, when calculating the detrital and non-detrital concentrations of Si, we have used 3.47 as the detrital Si/Al ratio.

The concentration trend for non-detrital SiO_2 in Lake Ala Lombolo resembles that in Lake Sakajärvi in that there is an evident decline towards the surface (Fig. 6a). As in the other two lakes, the variation of non-detrital SiO_2 concentration follows the variation in Si/Al (Si/Ti) ratio (Fig. 6b). In Fig. 7, the change of diatom concentration in the sediment is shown together with the non-detrital SiO_2 concentration. A dated (^{210}Pb) core from Lake Ala Lombolo suggests that the sedimentation in this lake has proceeded at a rather constant rate throughout the core (Pontér 1993). The decrease of non-detrital SiO_2 can thus not be referred to as a result merely of dilution by another type of material. The reason could instead be either increased dissolution of diatom frustules and subsequent removal through pore water diffusion, or a decreased sedimentation flux of non-detrital SiO_2 because of a declin-

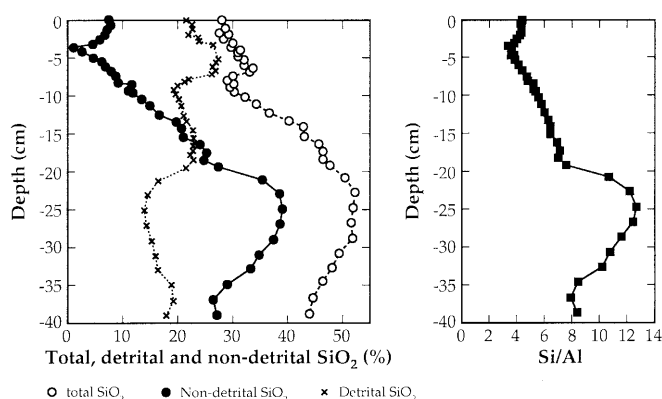


Fig. 6 Sediment from Lake Ala Lombolo. **a** The concentrations of total, non-detrital and detrital SiO_2 vs depth. **b** The molar Si/Al ratio vs depth

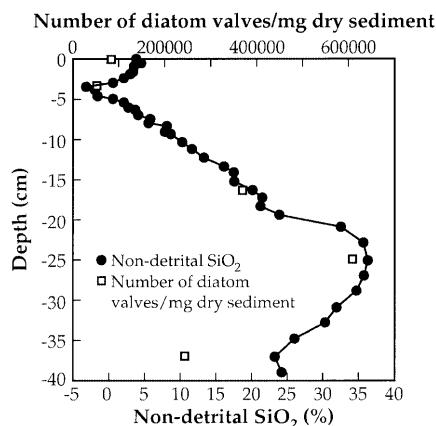


Fig. 7 The non-detrital SiO_2 concentration (%) and the diatom concentration (valves/mg dry sediment) in the sediment from Lake Ala Lombolo

ing diatom production. In any case, the concentration of non-detrital Si has decreased from making up more than a third of the dry weight of the sediment to zero, and to maintain a constant total sedimentation rate, there must have been an increase of some other phase. The total sedimentation flux (see discussion on Lake Sakajärvi above), calculated using the sedimentation rate of 0.27 cm/year , calculated using the dated core, is shown together with the fluxes of non-detrital SiO_2 and C in Fig. 8. The decrease in non-detrital SiO_2 is to some degree balanced by an increase in organic material. This increase has been possible as a consequence of the increasing nutrient concentrations in the lake. The redox conditions have become more reducing, and the decomposition of organic matter less efficient. However, it is notable that much of the non-detrital SiO_2 decrease is not compensated for by increases of other phases, but instead the porosity has increased (Fig. 9), implying that the total sediment flux has decreased. At 5 cm depth, the porosity

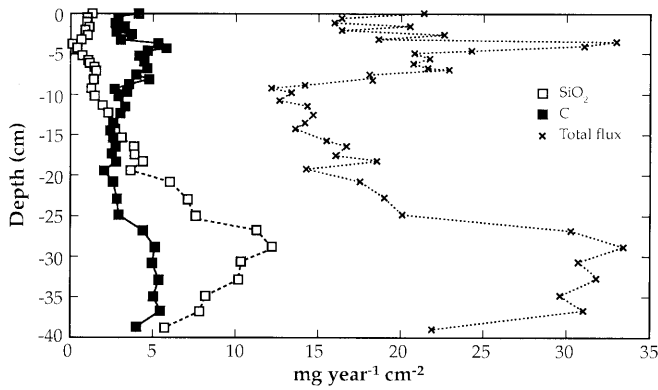


Fig. 8
The total annual sedimentation flux and the annual flux of non-detrital SiO₂ and C, mg year⁻¹ cm⁻²

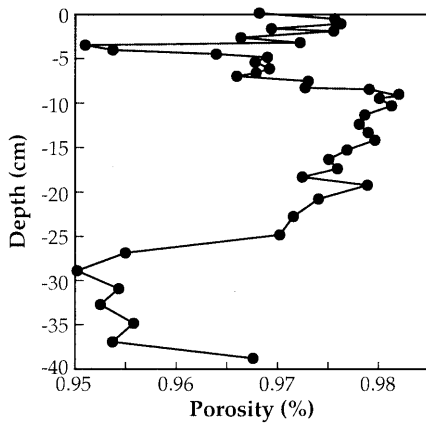


Fig. 9
The porosity vs depth in the sediment from Lake Ala Lombolo

again reaches low values whereas the concentration of C is at its highest.

Considering the pore water profile of dissolved Si (Fig. 10), an increased dissolution of diatom frustules does not seem likely. Si diffuses upwards through the sediment from at least 30 cm depth. An increasingly intense dissolution towards the sediment surface would be reflected in pore water profiles with maxima closer to the surface. For reference, the dissolved pore water Si concentration from the sediment of Lake Kutsasjärvi is also shown in Fig. 10. They both show a similar pattern. The second alternative, a decreasing diatom production, could be explained by the radical changes in water chemistry that have occurred because of human activities. The water chemistry in Lake Ala Lombolo is characterized by a relatively high concentration of total dissolved solids ($[Ca^{2+}] + [Mg^{2+}] + [Na^+] + [K^+] + [Cl^-] + [SO_4^{2-}] + [HCO_3^-] + [SiO_2(aq)]$): the average value during the ice-free season is 211 mg/l (corresponding values for Lakes Kutsasjärvi and Sakajärvi are 14.1 and 29.5 mg/l, respectively). Lake Ala Lombolo has high metal concentrations resulting from mining, as well as high concentrations of

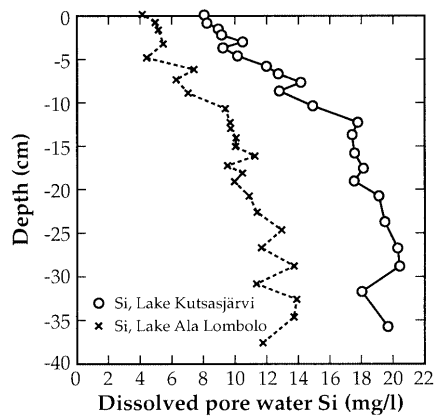


Fig. 10
Dissolved Si in the porewater of sediments from Lake Ala Lombolo and Lake Kutsasjärvi

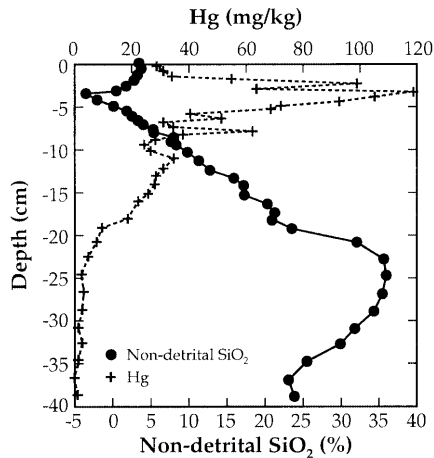


Fig. 11
Concentrations of Hg (mg/kg) and non-detrital SiO₂ (%) in sediment from Lake Ala Lombolo

nitrogen from explosives and phosphorus from apatite. Furthermore, municipal sewage was drained into Ala Lombolo until 1967. Enhanced concentrations of metals and nutrients are both factors known to affect the species composition of the algal community. Patrick (1978), among others, has shown, that diatoms are sensitive to changes in concentrations of several trace metals. Increased metal concentrations have been recorded in the sediment. Figure 11 shows the variations of the Hg concentration in the sediment, together with the non-detrital SiO₂ concentration. As the Hg concentration starts to increase at ~20 cm depth, the non-detrital SiO₂ concentration declines. V, Cr, Mo, Ni and As all have similar concentration trends. These changes coincide well in time with the onset of mining at the turn of the century. The concentrations of N and P in the sediment also increase at the same depth as the decrease of SiO₂ (Fig. 12). The concentration of non-detrital SiO₂ is zero at 4 cm depth, implying that the diatom production has virtually ceased.

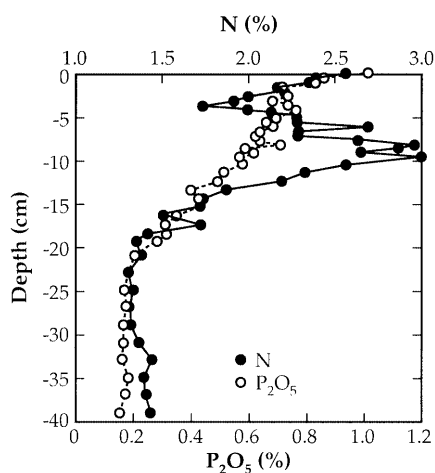


Fig. 12
N (%) and P₂O₅ (%) in sediment from Lake Ala Lombolo

The increasing trend in the top 4 cm suggests that the diatom population is beginning to recover, possibly as a result of the cessation of the sewage drainage into the lake.

Studies of the pelagic diatoms in Lake Ala Lombolo point to a disturbed diatom production. Compared with both Lake Kutsasjärvi and Lake Sakajärvi, the diatom bloom in Lake Ala Lombolo has, firstly, a shorter prolongation and is, secondly, smaller expressed as number of cells per litre (Fig. 13). It is well-known that eutrophication of lakes favours green algae and cyanobacteria over diatoms. High dissolved Si/P ratios have been shown to favour diatoms over other algae (Sommer 1988). In Lake Ala Lombolo, the Si/P ratio is considerably lower than in both Lake Sakajärvi and Lake Kutsasjärvi (molar ratio 220 ± 110 compared with $1,930 \pm 780$ and $1,930 \pm 940$, respectively, during the sampling period). The Si/P ratio in Lake Ala Lombolo shows a temporal variation, with the highest values during early summer (Fig. 14). Later, as the diatom bloom is over, the Si/P ratio decreases. The concentration of dissolved Si decreases continually from ice break-up until the end of July (Fig. 14). However, it does not fall below 1.6 mg/l, and should therefore not limit diatom growth (see for example Ahlgren 1970; Bailey-Watts 1976). The low Si/P ratio, perhaps in combination with high metal concentrations, is probably the reason for the abrupt decline of the diatom population in Lake Ala Lombolo (mainly *Diatoma tenuis* Agardh), being replaced primarily by the green alga *Tetraëdron minimum* (A. Braun) Hansgirg.

Conclusions

Despite the similarities in the variations of non-detrital Si in the sediments of Lake Sakajärvi and Lake Ala Lombolo, the causes for these variations are probably not the

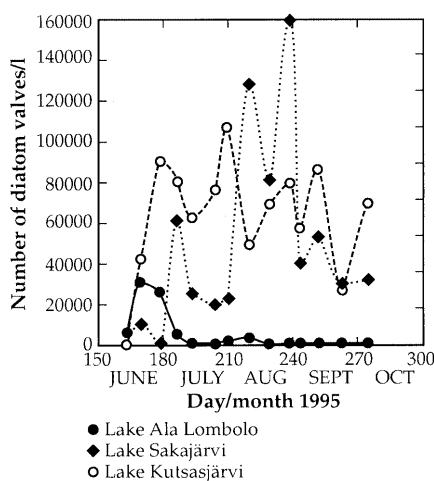


Fig. 13
The course of the pelagic diatom blooms in Lake Ala Lombolo, Lake Sakajärvi and Lake Kutsasjärvi during 1995

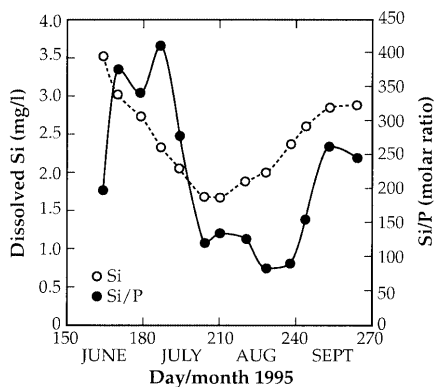


Fig. 14
The dissolved Si concentration (mg/l) and the dissolved Si/P molar ratio in Ala Lombolo during the ice-free period 1995

same. In Lake Ala Lombolo, the cause seems to be of biological character: a seriously disturbed diatom production in a lake where diatoms once made up about a third of the dry weight of the sediment. In Lake Sakajärvi, on the other hand, the declining concentration of non-detrital Si is largely the result of a higher degree of dilution caused by an increased sedimentation rate of detrital matter. The sediment from Lake Kutsasjärvi exhibits a different pattern. Here, the most important factor that influences the non-detrital Si concentration appears to be dissolution of buried diatom frustules, partly controlled by redox conditions.

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